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ABSTRACT

Two procedures for evaluating minehunting sonar performance are presented. One for detection with respect to range, the other for detection with respect to CPA or athwartships distance. Both procedures consider the trials results as subsets of normally distributed data and use fitted normal curves to calculate cumulative probability of detection curves which can be then assessed against specification.

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Executive Summary

The effectiveness of a minehunting sonar is dependent on detection performance in both along track (range) and in across track (athwartships) directions. Assessment against specification entails conducting many detection runs against known targets and statistical analysis of results.

This document proposes two new methods for assessing trials results against specification. The first method, used for detection range trials, is regarded as an improved methodology over a current procedure. The conclusions drawn using the new methodology are more reliable, and better reflect the true performance of the sonar.

The second method is applicable for evaluation of detection width trials and puts in place a formal methodology for data analysis. The equal area principle, defined by the conventional parameters A (swath width) and B (probability of detection), is applied to the processed data to compare results to the performance specification.

Contents

1. Introduction

The detection performance of minehunting sonars is usually assessed by conducting detection trials against known targets in a known or measured environment. Due to limitations of time and cost the number of detection runs has to be minimised, subject to validation of statistics, for each trial objective. Normally, 25 to 30 runs are planned for each trial and conclusions about the sonar performance must be drawn from these 25 or 30 samples. How to make reliable statistical inference is crucial in the trials analysis.

In this document, two methodologies are established for evaluating the detection performance of a minehunting sonar. The first method is appropriate for Detection Range Trials (DRT) that are designed to assess the detection performance as a function of range ahead of the vessel. The second method is developed for Detection Width Trials (DWT) where the detection capability against across track distance is evaluated. Implicit in the assessment trials is the assumption that the results from a limited number of runs are representative of the sonar performance in general. That is, a comparatively limited number of runs are representative and statistically valid samples from the set of all possible detection runs. Typically 25 to 30 runs are conducted for detection range trials. Many more runs are needed for detection width trials to ensure sufficient samples at all cross track range intervals.

An evaluation methodology for detection range trials has been described by Thompson and Bell 1997 [1]. This procedure was used effectively during trials of the RAN Mine Hunter Inshore (MHI). In this paper, the methodology is improved by clarifying mathematical relationships between the detection range and the probability of detection. It is important to note that the probability of detection of a target, and the range at which a certain probability of detection is achieved are two different concepts. In order to compare trials results to the performance specification it is necessary to combine both these factors.

Thompson and Bell use a cumulative probability of detection against range to quantify the sonar performance [1], however the definition of probability of detection is valid only if there is no failure in the detection runs and the target is detected on all possible encounters. The procedure does not satisfactorily account for non-detections (misses) as it sets the range to zero for runs where no detection is made. The methodology is, by this definition, insufficiently robust to handle the situation when one or more detection runs fail because the cumulative probability of detection was not based on any density functions.

The methodology presented here for the detection range trials is considered a more accurate and reliable procedure than that of Thompson and Bell and as a result, the conclusions drawn from the trials results fairer. This is particularly so for a limited number of detection runs (small number of samples), and for un-indicated trials where

detection may not be achieved in some runs. The crux of the method is that the cumulative probability of detection is defined implicitly by the Cumulative Distribution Function (cdf) of the ranges at which detections occur. It is possible therefore to determine the Probability Density Function (pdf) of the detection range and from this the corresponding cumulative distribution function.

For detection width trials a second methodology is established for measurement of the probability of detection with respect to Closest Point of Approach (CPA). The concept is straightforward, first determining detection probability as a histogram with respect to the lateral displacement of a target from the ship's track, and second, using curve fitting to obtain a smoothed curve that represents properties of the sample population. The *area equal principle* is then used to compare the result generated against the performance criteria.

Confidence intervals for both methodologies are addressed but as yet the significance for detection width trials is not properly understood.

2. Interpretation of Trials Specification

The trials procedure is designed to demonstrate that the sonar meets performance criteria in accordance with the specification. Typically, for detection range trials, the specification will require that the sonar shall detect, at a certain probability of detection, a given type of target at ranges greater than some defined distance. We need to determine what does this really mean and how should we interpret the requirement? For example, the specification may indicate the sonar is capable of detecting mine of target strength X at ranges greater than 500 metres ($r \geq 500$ m) at a probability of detection P_d = 0.9, from 10 to 100 metres depth over a sand seabed type. This P_d is defined by *m/N*, where *m* is the number of detections and *N* is the number of runs.

This specification can be satisfied by two limiting results that define the extremes of satisfactory outcomes. If all runs score hits and no misses occur (P_d = 1), then at least 90% of the detections must be at ranges $r \geq 500$ m. Conversely if there are 10% misses (P_d=0.9), then 100% of detections achieved must be at ranges $r \geq 500$m. Generally the result lies in between these limits and we have to determine which parameter varies, r , P_d or both.

For detection width trials the conventional parameters *A* and *B*, as defined in the NATO publication ATP-6 (B) [2], are given in the specification. Parameter *B* is the height of a trapezoid or rectangle (ie,. the probability of detection) and parameter *A* is the width of the trapezoid at one-half *B* or the width of rectangle (ie, detection width). For example, the sonar specification may require detection of specified targets at a

probability of 0.9 over a swath width of 200 metres. That is $B = 0.9$ for A=200. Since the parameters A and B determine a unique area, the methodology for determining whether trials results meet the specification can be based on a comparison of areas as described in the following section.

3. Methods for Evaluating Performance

A sonar detection trial consists of a number of detection runs and each run includes at least one planned encounter between the minehunter sonar and a mine. If detection fails (ie, an encounter is not marked by the sonar operator), the result is a 'miss'. Otherwise, it is a 'hit'.

The objective of detection range and detection width trials is to draw conclusions on the actual distribution of hits and misses, and the locations of those hits, from the empirical (sample) distributions obtained during the limited number of detection runs. By combining results from previous experiments and the data from the trial, one can usually postulate the general nature of the frequency distribution. From probability theory, for independent trials, which is the case here, the premise that the possible outcomes in the trial will occur equally often implies that a large number of runs will yield the probability distribution for the general case. Thereafter, one can draw conclusions on whether the specification is satisfied.

One means of assessing detection performance is to quantify the trials data on a plot of probability of detection against range of detection. By comparing the curve so generated with the sonar specification, conclusions on the success or failure of the trials results can be drawn. This raises the question, how to establish a relationship between P_d and detection range which reflects the specification requirement? Essentially, a cumulative distribution function of the detection range, scaled by a measured $\hat{P}_d$, is required.

3.1 Detection Probability With Respect to Range

The probability of detection can be estimated by the frequency of the hits against the number of encounters. That is, P_d is determined from the set of possible encounters. We are also interested in the ranges at which hits occur since these constitute the other parameter in the detection vs range curve. This range is also a random variable defined in this case on the domain formed by the subset of encounters corresponding to the hits. Hence, P_d cannot be defined as a simple function of the range. Indeed, we have a graphic expression (figure 1) showing the probability of detection as a function of range for a single ping. However, this probability is not the P_d discussed here. It is a conditional probability function, which indicates a probability that a target at a certain

range can be detected by a single ping. It cannot be integrated along the range to obtain a cumulative P_d because the curve is not a probability density function (pdf).

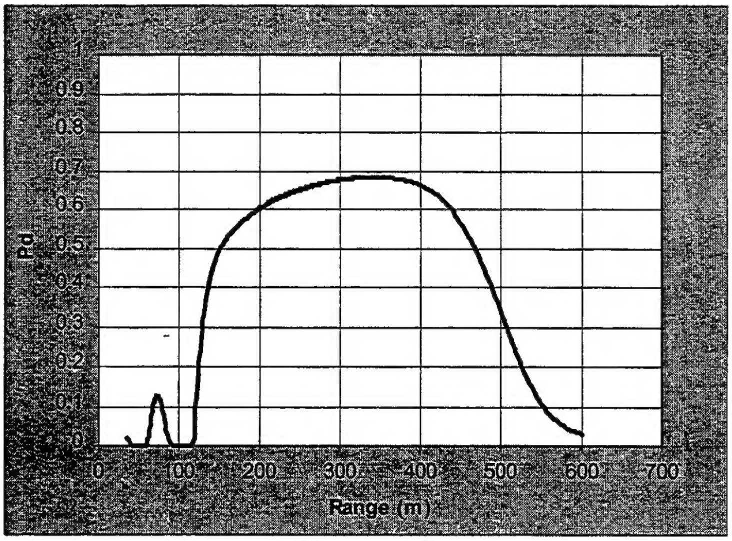

Figure 1. The probability of detection as a function of range for a single ping.

To demonstrate the analysis we use the same example given by Thompson and Bell for a detection range trial with a total of 20 detection runs. A set of 20 ranges is logged due to no misses (Table 1). Hence, both m and N are 20 and $\hat{P}_d = m/N = 1$. The minimum and maximum ranges are 157 m and 507 m.

Table 1 . Typical DRT log

Run Number	Detection Range (m)	Run Number	Detection Range (m)
1	319	11	431
2	253	12	507
3	270	13	389
4	312	14	421
5	359	15	378
6	157	16	409
7	217	17	341
8	230	18	328
9	351	19	318
10	450	20	298

A range class interval for the analysis is chosen depending on how precisely the range distribution is to be analysed. After the class boundaries have been determined it is a simple matter to locate each of the measured ranges in the proper class interval. All ranges between the limits and including the (closed) upper limit are placed in the same class, and the number detection ranges for each class interval recorded. The raw data are then classified. Table 2 illustrates the classification and distribution of ranges from the above detection range trial when a 50 metre class interval is selected. The interval width can be varied depending upon the number of samples. In general, 50 - 100 metres is appropriate to 30 runs.

Table 2. Frequency Table

Class Boundaries (m)	Numbers	Frequencies
50 - 100	0	0
100 - 150	0	0
150 - 200	1	0.05
200 - 250	1	0.05
250 - 300	3	0.15
300 -350	4	0.20
350 - 400	4	0.20
400 - 450	4	0.20
450 - 500	2	0.10
500 - 550	1	0.05
550 - 600	0	0
Total	20	1.0

The data of Table 2 are illustrated graphically in Figure 2, which shows a histogram of the distribution of 20 detection ranges.

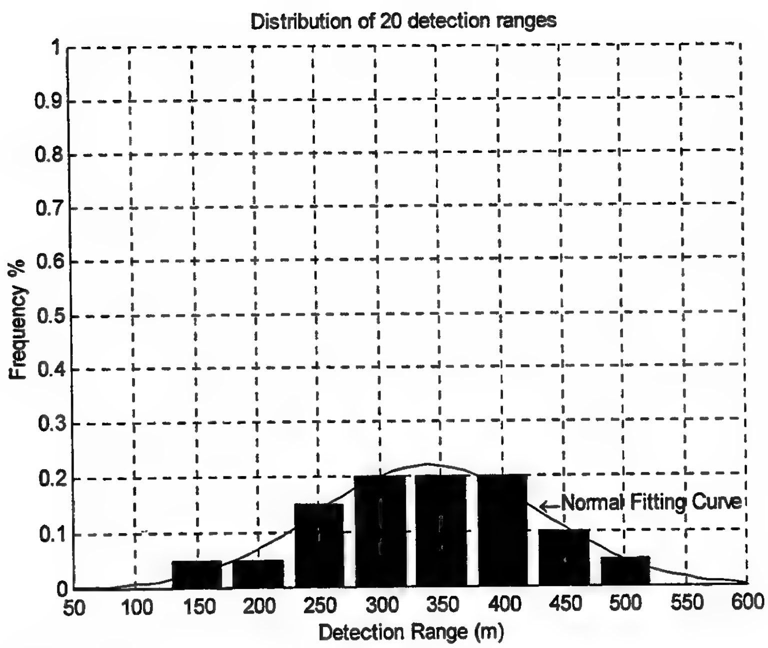

Figure 2. Distribution of detection ranges for the DRT's data in Table 1.

In order to draw conclusions about the detection range for the trial several questions need to be addressed. First, what kind of distribution do the detection range data follow, and second, how are we to draw conclusions about the trials results? Should a cumulative distribution function be generated directly from the raw histogram or should it be obtained after first smoothing?

The detection range can be thought of as a continuous variable that can assume any value over the range interval from zero to the maximum of the sonar range scale. If we conducted a large number of detection runs, the results should converge to a distribution representative of the population. In as much as the detection range is determined by many factors, none of which is dominant, a normal distribution is assumed with its mean > 0. (This assumption is supported by evidence from many previous trials that demonstrate that the detection ranges approximate a normal distribution.) Hence, if the number of runs for the trial is statistically valid, using a normal curve to approximate the histogram seems a reasonable approach to estimating the sonar performance.

A fitted normal curve is shown in Figure 2. It is a probability density function (pdf) of detection range (the value in x-axis was normalised in deriving the standard deviation). Finally, the associated cumulative distribution can be calculated from the mean and standard deviation which, in this example, are 339 m and 130 m respectively.

Since in this method only data corresponding to runs achieving hits are considered in the analysis, the cumulative distribution function obtained by integrating the fitted normal curve over the range interval always scales to one. The curve must be scaled to

reflect the true detection probability achieved during the trial by multiplying by the $\hat{P}_d$ obtained by dividing the number of hits by the number of runs. For the data in table 1 no misses were recorded so $\hat{P}_d$ is 1. In addition, the range is accumulated in an inverse order to give the traditional detection probability curve for minehunting sea trials (Figure 3).

Each measured detection range is regarded as a sample of a normal population. When the standard deviation of the population is assumed to be the sample standard deviation, for large samples, the symmetric 100(1-α)% confidence interval for the expectation of a normal distributed range is $\bar{x} \pm z_{\alpha/2}\dfrac{\sigma}{\sqrt{N}}$, where σ is the standard deviation of the distribution and N is the number of samples. (For a 95% confidence interval, $z_{0.025}$ = 1.96 if N *is* large). For small N, as is the case in this example, confidence intervals should be calculated from Student's *t-distribution* instead of the normal distribution (for details see Appendix 1). For the data in Table 1, $\bar{x} = 337$ and σ = 122. Based on these results, we have the confidence limits shown in Figure 3.

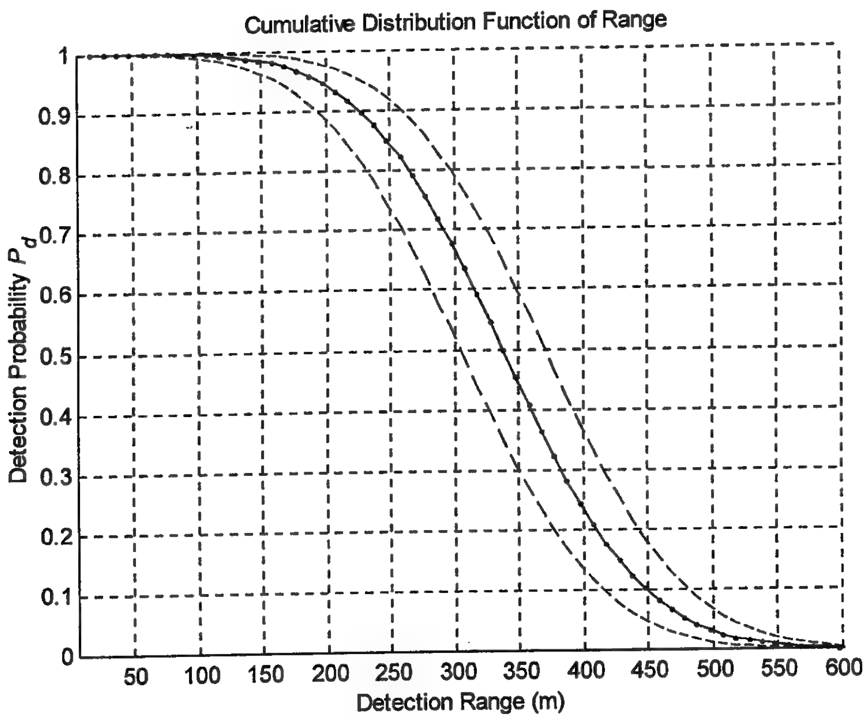

Figure 3. The Y-axis is the probability of detection P_d and the X-axis is the range of detection. The curve is a cumulative distribution function of the detection ranges scaled by $\hat{P}_d$. The dashed lines are the upper and lower 90% confidence limits for the example data in Table 1.

3.2 Detection Probability With Respect to Closest Point of Approach, DWT

The aim in detection width trials is to determine the distribution of detection ranges with respect to the lateral displacement of a target from the ship's track. This kind of trial requires a large number of encounters to ensure sufficient samples at all cross track range intervals and reliability of statistical results.

The following example describes a procedure for processing data from detection width trials. The CPA for each planned encounter is calculated based on known ship and target positions. The CPAs of all the planned encounters and of those achieving hits are grouped according to athwartship range interval as in Table 3. The probability of detection is then calculated at each range interval.

Table 3. Distribution of planned encounters and data measured from a DWT.

Athwartship distance (m)	Number of encounters	Number of Hits	Detection Probability
-300	4	0	0
-250	4	0	0
-200	10	0	0
-150	9	3	0.33
-100	11	2	0.18
-50	27	7	0.26
0	25	24	0.96
50	18	15	0.83
100	19	17	0.89
150	24	4	0.17
200	11	2	0.18
250	9	0	0
300	5	0	0
350	8	0	0
Total	184	74	-

The data in Table 3 are shown as a histogram in figure 4(a). The dark bars illustrate the distribution of the planned encounters with respect to the CPA. The light bars show the distribution of detections achieved with respect to CPA. For the above example, results for P_d will be inaccurate at large CPA because the sample population is too small, and hence the reliability of the estimate is poor. This illustrates that in planning detection width trials it is important to consider the distribution of encounters to ensure sufficient encounters in all range intervals. In order to obtain an equal reliability across lateral range we need to plan for a uniform distribution for encounters.

The histogram of P_d is shown in Figure 4 (b), and a normal curve is fitted. As indicated, the distribution of measured P_d along the athwartships distance is not

always normal, although it is true in general and particularly for large numbers of samples. As for the detection range trials, this P_d curve is not a probability density function of P_d but a conditional probability function that gives the probability of detection at a certain CPA. The normal function is assumed in the form:

$$P_d(x) = \alpha \cdot e^{-(x-\mu)^2/\omega^2}$$

which, in this example gives $\alpha = 0.98$, $\mu = 0$ and $\omega = 102.37$.

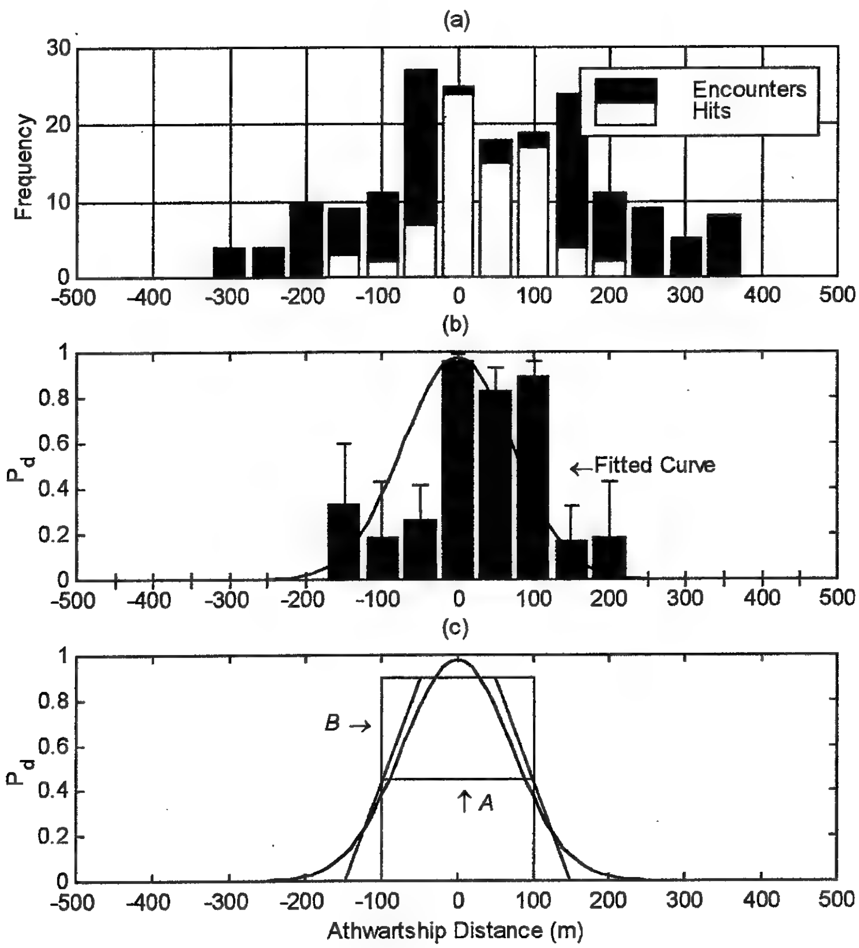

Figure 4. The probability of detection with respect to athwartships distance. (a) Shows the distributions of encounters and hits; (b) gives the histogram of P_d and data error bars; and (c) demonstrates fitted curve of P_d and the specification of the DWT by the trapezoid or rectangle.

If we put the specification, say, $A = 200$ m and $B = 0.9$, in Figure 4 (c) then an aggregate detection width (the area defined by $A \times B$ in Ref [2]) is illustrated by the trapezoid or rectangle. In general, the fitted curve will not satisfy the specification graphically. To quantify a measure against the specification, the *Equal Area Principle* of Politt 1992 [3] can be applied. If the area under the curve is greater than or equal to the area of the trapezoid or rectangle, the specification is met. In practice there may be a small bias in the trials results and a direct fitted curve may be displaced left or right of the centre line. By ignoring this random bias, one can fit data by setting the mean to be zero. If this bias is significant it should be investigated further.

Now, we consider the confidence interval of P_d. The P_d curve is assumed in general to be a normal distribution, especially for large samples. As a large number of encounters will be planned for the detection width trials, the mean of the curve will be close to zero and variation of the standard deviation will not be significant as the number of samples varies. We are not interested in the confidence intervals for the normal feature itself. We do however care about the accuracy of the value of P_d in each bin where the binomial distribution is applied. For the bins at large athwartships distances, large errors of P_d are expected due to the small number of samples for each bin. As a result, a large confidence interval will be generated at the edges of the histogram where there are limited samples. This is illustrated by the error bars in Figure 4(b). (Procedures for calculating the confidence interval are given in Appendix 2.)

In this example, the area required by the specification is $A \times B$ = 180 m^2, but the total area under the curve of P_d is 177.6 m^2. The results of this trial therefore indicate a failure.

Another consideration is, should we form an upper confident limit as we did for the detection range trials? It seems inappropriate to assess results using the area under the upper limit, because that area will be large if the error in the estimate of P_d is large, and the assessment yardstick therefore inaccurate.

4. Results Comparisons for Detection Range Trials

In this section, four examples are demonstrated to compare results using the previous method and the method proposed. The curve generated by using procedures described in this paper is shown as the thick line in each figure. The upper and lower 90% confidence limits are determined according to required confidence level and the number of samples using Table 4 of Appendix 1. The thin lines with dots are the curves determined using the methodology in Ref [1].

The results from the two methods basically match when all runs achieve hits and $\hat{P}_d$ is one, however the agreement between the procedures decreases as $\hat{P}_d$ reduces. This is because the definition of P_d in Ref [1] is inadequate if the target is not detected on a number of runs. The new result is more robust and more reliable statistically (Figure 5 and Figure 6), and it is less susceptible to aberrations in the curve due to outlying data points. When the difference between the methodologies becomes significant the reliability of the new method is crucial in determining the most appropriate procedure.

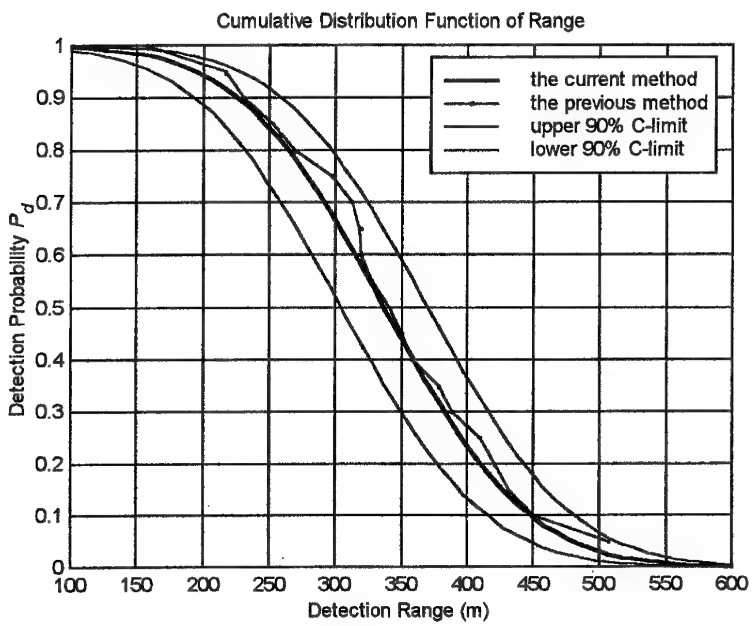

Figure 4. Example 1: Minehunting sonar performance for the DRT. The curve calculated by current method is compared with one from the previous method. Data used are given in Table 1. There are 20 runs and 20 hits, therefore $\hat{P}_d$ = 1.0. For N =20 and 90% confidence interval, k=0.39 (see Appendix 1).

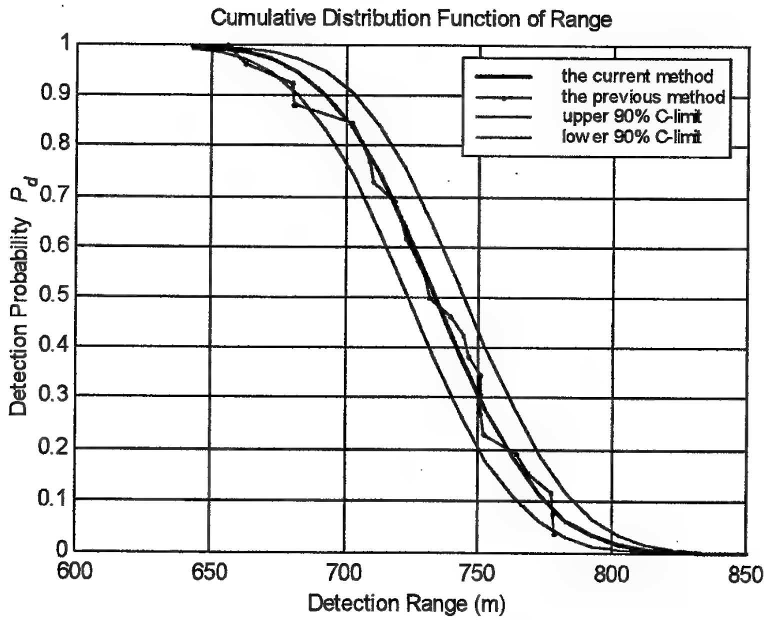

Figure 6. Example 2: Minehunting sonar performance for the DRT. Data used are in Appendix 3, Table 5. Where N=26 and m=26, $\hat{P}_d = 1.0$. k=0.34 for 90% confidence interval.

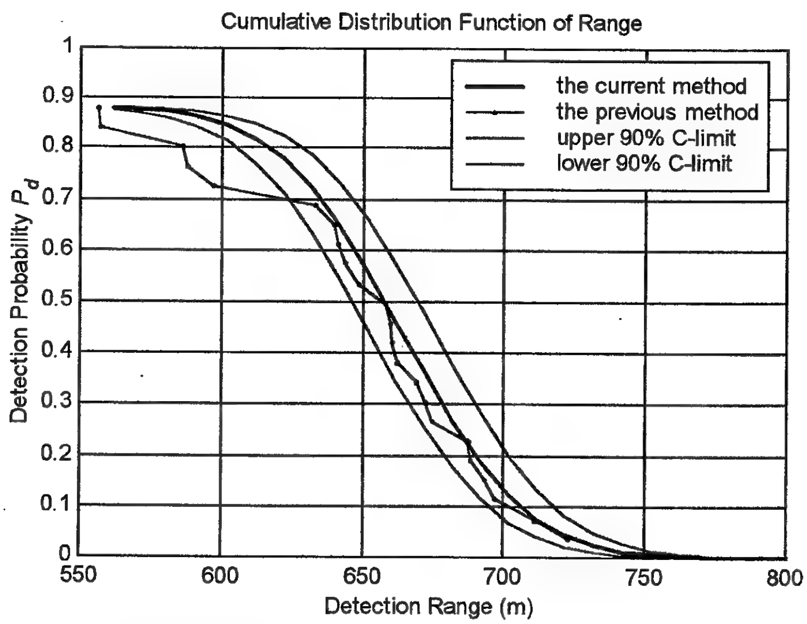

Figure 7. Example 3: Minehunting sonar performance for the DRT. Data used are in Appendix 3, Table 6. When N=26 and m=23, $\hat{P}_d = 0.88$. k=0.34 for 90% confidence interval.

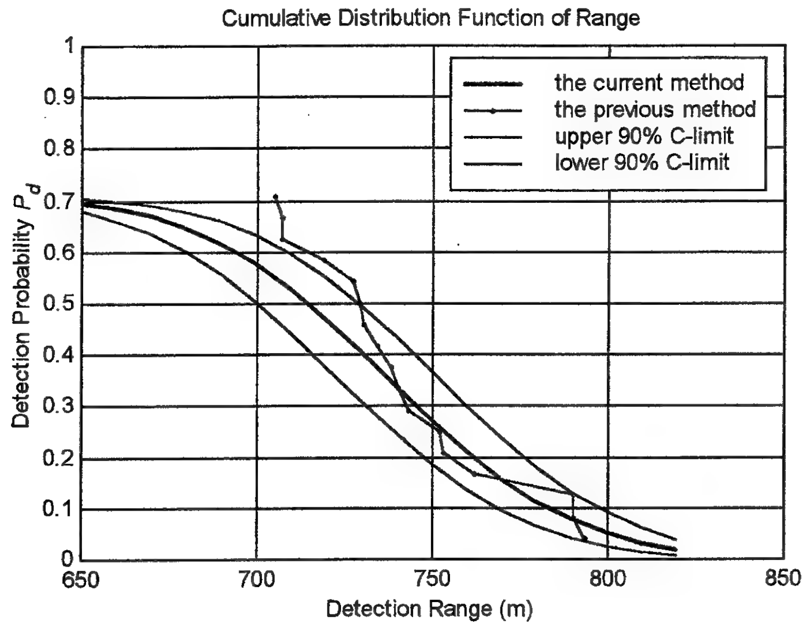

Figure 8. Example 4: Minehunting sonar performance for the DRT. Data used are shown in Appendix 3, Table 7. N=24 and m=17, hence $\hat{P}_d$ = 0.71. k=0.35 for 90% confidence interval.

Figures 7 and 8 illustrate effect of scaling by the $\hat{P}_d$ achieved during the trial. For figure 7, which corresponds to Table 6 in appendix 3, 23 detections were made in 26 runs, hence $\hat{P}_d$=0.88. For the data in Table 7, 17 hits were achieved in 24 runs. In this case $\hat{P}_d$=0.71 and the curves in figure 8 are scaled accordingly.

5. Conclusion

Two methodologies have been described for evaluation of minehunting sonar performance. The first, used for detection range trials, is regarded as an improved methodology over that described by Thompson and Bell [1]. The conclusions drawn using the new methodology are more reliable, and better reflect the true performance of the sonar and consequently a more reasonable judgment of the sonar performance.

The second methodology is applicable to evaluation of detection width trials. The equal area principle is applied to the processed data to reflect the system requirement. The question should an upper confident limit be used remains open.

As a large number of encounters is needed in detection width trails to ensure statistical reliability, it is suggested that the trials procedures outlined in the RAN Minehunter Coastal Contract [4] be reassessed in light of this requirement.

6. References

1. Thompson, J.L. and Bell, M.J. '*Evaluation of the performance of a Minehunting Sonar*', DSTO-TN-0123, 1997.
2. ATP-6 (B), '*Mine Countermeasures Operations Planning and Evaluation*', Vol II, 1991. (NATO CONFIDENTIAL).
3. Pollitt, G., Unpublished notes on mine hunting. 1992.
4. RAN Minehunter Coastal Contract C218481, *Attachment 1: Minehunter Coastal Sonar Performance Trials Procedure*, 1995.

Appendix 1

When the sample size N *is less than* 30, problems of confidence interval are based on small sampling theory. Most sea trials belong to this category. For detection range trials the standard deviation of range is generally unknown. If the mean μ for range follows a normal distribution $N(\mu,\sigma)$, then its pivot variable $\frac{\bar{x}-\mu}{\hat{s}}\sqrt{N}$ follows Student's t distribution $t(N\text{-}1)$, where $\hat{s}$ is the sample standard deviation. As is done with the normal distribution for confidence intervals $\bar{x} \pm z_{\alpha/2}\frac{\sigma}{\sqrt{N}}$, for small samples we replace $z_{\alpha/2}$ (obtained from the normal distribution) by $t_{\alpha/2}$ (obtained from the t distribution), then a 99%, 98%, 95% and 90% confidence interval for μ can be calculated by

$$\mu = \bar{x} \pm k \cdot \hat{s}$$

The factor k ($\sim t_{\alpha/2}/\text{N}$), determined by using Student's t-distribution with ν degrees of freedom, is taken from table 4 below:

Table 4. Confidence interval for the expectation of a normal distribution from a small samples with ν degrees of freedom.

ν	N	$t_{0.005}$ k (99%)	$t_{0.01}$ k (98%)	$t_{0.025}$ k (95%)	$t_{0.05}$ k (90%)
1	2	45.01	22.50	8.99	4.46
2	3	5.73	4.02	2.48	1.69
3	4	2.92	2.27	1.59	1.18
4	5	2.06	1.68	1.24	0.95
5	6	1.65	1.37	1.05	0.82
6	7	1.40	1.19	0.93	0.73
7	8	1.24	1.06	0.83	0.67
8	9	1.12	0.97	0.77	0.62
9	10	1.03	0.89	0.71	0.58
10	11	0.96	0.83	0.67	0.55
11	12	0.90	0.79	0.64	0.52
12	13	0.85	0.74	0.60	0.49
13	14	0.80	0.71	0.58	0.47
14	15	0.77	0.68	0.55	0.45
15	16	0.74	0.65	0.53	0.44
16	17	0.71	0.63	0.51	0.42
17	18	0.68	0.61	0.50	0.41
18	19	0.66	0.59	0.48	0.40
19	20	0.64	0.57	0.47	0.39

ν	N	$t_{0.005}$ k (99%)	$t_{0.01}$ k (98%)	$t_{0.025}$ k (95%)	$t_{0.05}$ k (90%)
20	21	0.62	0.55	0.46	0.38
21	22	0.60	0.54	0.44	0.37
22	23	0.59	0.52	0.43	0.36
23	24	0.57	0.51	0.42	0.35
24	25	0.56	0.50	0.41	0.34
25	26	0.55	0.49	0.40	0.34
26	27	0.54	0.48	0.40	0.33
27	28	0.52	0.47	0.39	0.32
28	29	0.51	0.46	0.38	0.32
29	30	0.50	0.45	0.37	0.31
30	31	0.49	0.44	0.37	0.31

Appendix 2

In a given bin, we assume that m hits were observed in n detection runs. It is a Bernoulli trial with a binomial probability distribution. If we use $\hat{p} = m/N$ to approximate the probability of detection, the approximate 100(1-α) % symmetric confidence interval is

$$\hat{p} \pm z_{\alpha/2}\sqrt{\frac{\hat{p}(1-\hat{p})}{N}}$$

Here $z_{\alpha/2}$ is the $100(1-\alpha/2)^{th}$ percentile with typical values of 1.645, 1.96 and 2.575 corresponding to the 90%, 95% and 99% confidence levels respectively.

Appendix 3

Table 5. The DRT data for example 2 in Section 4.

No.	Range (m)	Detection Status
1	656	Y
2	662	Y
3	671	Y
4	680	Y
5	702	Y
6	706	Y
7	709	Y
8	710	Y
9	718	Y
10	721	Y
11	723	Y
12	727	Y
13	730	Y
14	731	Y
15	739	Y
16	744	Y
17	746	Y
18	750	Y
19	751	Y
20	751	Y
21	752	Y
22	764	Y
23	768	Y
24	777	Y
25	778	Y
26	778	Y
	P_d	1.0

Table 6. The DRT data for example 3 in Section 4.

No.	Range (m)	Detection Status
1	0	N
2	0	N
3	0	N
4	556	Y
5	557	Y
6	586	Y
7	588	Y
8	597	Y
9	633	Y
10	640	Y
11	641	Y
12	644	Y
13	649	Y
14	658	Y
15	660	Y
16	660	Y
17	662	Y
18	669	Y
19	672	Y
20	674	Y
21	687	Y
22	688	Y
23	693	Y
24	697	Y
25	711	Y
26	723	Y
	P_d	0.88

Table 7. The DRT data for example 3 in Section 4.

No.	Range (m)	Detection Status
1	0	N
2	0	N
3	0	N
4	0	N
5	0	N
6	0	N
7	0	N
8	705	Y
9	707	Y
10	707	Y
11	719	Y
12	727	Y
13	729	Y
14	730	Y
15	734	Y
16	738	Y
17	740	Y
18	743	Y
19	752	Y
20	753	Y
21	762	Y
22	790	Y
23	790	Y
24	793	Y
	P_d	0.71

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P. Cao and M.J. Bell

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19. ABSTRACT

Two procedures for evaluating minehunting sonar performance are presented. One for detection with respect to range, the other for detection with respect to CPA or athwartships distance. Both procedures consider the trials results as subsets of normally distributed data and use fitted normal curves to calculate cumulative probability of detection curves which can be then assessed against specification.

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